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Cost and Performance Report

(WP-0202)

Electrospark Deposition for Depot- and Field-Level Component Repair and Replacement of Hard Chromium Plating

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ACRONYMS AND ABBREVIATIONS

ALC	Air Logistics Center
ANAD	Anniston Army Depot
ARDEC	Armament Research and Development Engineering Center
ARL	Army Research Laboratory
ASAP	Advanced Surfaces and Processes, Inc.
ASTM	American Society for Testing and Materials
CBA	cost-benefit analysis
cermet	ceramic/metal
Cr	chromium
DOD	Department of Defense
DOE	design of experiment
ECAM	Environmental Cost Analysis Methodology
EHC	electrolytic hard chrome
ESA	electrospark alloying
ESD	electrospark deposition
ESOH	environmental, safety and occupational health
ESTCP	Environmental Security Technology Certification Program
GEAE	GE Aircraft Engines
GTE	gas turbine engine
HAZ	heat-affected zone
H-S	Hamilton Sundstrand
HVOF	high-velocity oxygen-fuel
Hz	hertz (cycles-per-second)
IN625	Inconel 625 alloy
IN718	Inconel 718 alloy
IRR	internal rate-of-return
JTP	joint test protocol
ksi	thousands of pounds per square inch
LCF	low-cycle fatigue
MRB	Materials Review Board
MSDS	material safety data sheet

ACRONYMS AND ABBREVIATIONS (continued)

Ni	nickel
NLOS	non-line-of-sight
NPV	net present value
NSWCCD	Naval Surface Warfare Center Carderock Division
OC-ALC	Oklahoma City Air Logistics Center
OEM	original equipment manufacturer
OMB	Office of Management and Budget
OSHA	Occupational Safety and Health Administration
P&W	Pratt & Whitney
PEL	permissible exposure limit
PEWG	Propulsion Environmental Working Group
PPE	personal protective equipment
PSU	Portland State University
ROI	return on investment
rpm	rotations per minute
SBIR	Small Business Innovative Research
SERDP	Strategic Environmental Research & Development Program
SOR	source of repair
S-N	stress versus number of cycles (for fatigue data plots)
TO	technical order
µF	microfarad(s)
UIT	ultrasonic impact treatment
UTRC	United Technologies Research Center

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Military components are frequently damaged in service through corrosion, impact, or wear. They must be either repaired in the field (operational-level repair) or shipped back to the depot. When a localized repair is possible, it is usually done by brush plating nickel (Ni) or chromium (Cr) (using a Cr^{6+} solution). If the component cannot be repaired in the damaged area alone, the entire surface and any coating on it must be removed and rebuilt, usually by chrome plating or sulfamate Ni to reclaim dimensions followed by chrome plate for wear. When chrome plate is damaged, the only recourse for a permanent repair is to strip and replate. All these processes create hazardous waste and expose personnel to toxic materials.

In addition, there are many components that suffer significant damage and for which there is neither a field nor depot-level repair currently available. At present, these components must be condemned, resulting in costs associated with their replacement and disposal.

A technology that could replace brush plating and provide field repair on currently non-repairable parts would reduce waste generation, personnel exposure, and cost while improving readiness by returning components to service more rapidly.

Electrospark deposition (ESD), also known as electrospark alloying (ESA), is a microwelding technique that has demonstrated capability for filling damaged areas and restoring coating damage. It uses short-duration, high-current electrical pulses to weld a consumable electrode material to a metallic substrate. Since almost any alloy can be deposited, the method is ideal for filling damage over small areas, as in the case of localized wear or corrosion, using the same alloy as the parent metal. The heat generated in the process is very small, eliminating thermal distortion and allowing the process to be used on heat-sensitive materials. The equipment is small and portable and can be manually operated with a simple shroud to remove any fumes. The simplicity and cleanliness of the process allows it to be safely used by operators without extensive training for both depot-level overhaul and operational-level in-place repair.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective was to demonstrate ESD as a technically feasible and commercially viable production-scale process for localized repair of weapons systems components and to transition ESD repairs for use on Department of Defense (DoD) components for gas turbine engines (GTE), vehicles, and ships.

Demonstration sites were Oklahoma City Air Logistics Center (OC-ALC) and Anniston Army Depot (ANAD) (working with the Army Research Laboratory [ARL]). ESD units were acquired and placed in each of these facilities, and candidate components identified. The Naval Surface Warfare Center Carderock Divison (NSWCCD) evaluated the process for repair of submarine components under a parallel program. Because the potential usage was so broad, a complete Demonstration Plan incorporating a joint test protocol (JTP) was developed only for GTE applications working in conjunction with OC-ALC to qualify ESD for:

- Localized repair by depositing the same alloy material from which the component is manufactured
- Localized repair of chrome plating.

1.3 REGULATORY DRIVERS

The primary environmental, safety and occupational health (ESOH) issue is reduction of Cr^{6+} air emissions and waste discharges from processes such as chrome stripping, tank plating, and chrome brush plating. The Cr^{6+} permissible exposure limit (PEL) has recently been lowered by an order of magnitude, to 5 µg/m^3, with an action level of 2.5 µg/m^3. This will affect DoD repair operations, including tank and brush plating. The difficulty and cost of meeting this rule will be substantial and will help to drive the adoption of clean processes.

Component Testing and Qualified Repairs: Specific components investigated for ESD repair under the GTE Demonstration Plan included:

- TF33 10-12 stator segment fabricated from Inconel 718 (non-line of sight)
- TF 39 shaft fabricated from Inconel 718 (chrome plate repair)
- TF33 #5 bearing housing fabricated from 410 stainless steel (dimensional restoration).

Other applications at NSWCCD and ANAD included:

- Submarine steering and diving control rods fabricated from K-Monel
- Abrams tank M1A1 cradle fabricated from 4130 steel and helical gear shaft.

A repair was developed, qualified, and implemented at ANAD for the M1A1 Abrams tank gun barrel cradle. This process is now being used to recover about 12 cradles per year at an annual saving of approximately $300,000. This repair was developed by ANAD personnel based on a clear depot need, with minimal process development and operator training. A repair was also developed for an M1A1 turbine engine helical gear shaft. This repair will be qualified on successful completion of a 100-hr engine test. Local process specifications were written for operation and maintenance of the ESD process. Repair specifications were developed to ensure acceptable quality and a reproducible process.

ESD repair of the TF33 #5 bearing housing has been qualified at OC-ALC. Technical order (TO) changes have been made to allow this repair.

1.4 PROCESS AND EQUIPMENT DEVELOPMENT

During the course of the project, various process and equipment developments were made, including process optimization, robotic coating (which was compared with manual operation), and incorporation of ultrasonic impact treatment (UIT) to impart compressive stress to the ESD coating. The latter was found to improve fatigue and hardness.

1.5 DEMONSTRATION RESULTS

1.5.1 Process Development and Materials Testing

The substrate alloy used for materials testing was Inconel 718 (IN718). Electrodes of the same material were applied to each of these substrate alloys. In addition, IN718 specimens were prepared with an electrolytic hard chrome (EHC) coating, and the ESD electrode material was Inconel 625 (IN625).

ESD was used to fill spherical-bottom holes (divots) and spherical-bottom grooves. The process was characterized for deposition rate and coating quality—hardness, porosity, and discontinuities. The following data were obtained for IN718 filled with IN718:

- *Bond strength (American Society for Testing and Materials [ASTM] C633).* As expected for a weld process, the bond strength exceeded 10 ksi, with all failures in the glue.
- *Deposition rate.* Overall deposition rate was 1 to 7 mg/min, depending on conditions. This low deposition rate clearly demonstrates that the primary use of the process is localized repair rather than large-scale coating deposition.
- *Tensile properties.* Flat tensile bars with ESD-filled divots had yield and ultimate strengths within 2% of the undamaged material. Reduction in area was about 30% lower and elongation about 40% lower with a filled defect than in the virgin material. This shows that the use of ESD will not degrade the strength of repaired components.
- *Residual stress.* As with all weld processes, ESD coatings were tensile.
- *Fatigue.* In general, the fatigue curve for repaired material fell between that of the undamaged material and that of the damaged but unrepaired material. Thus the repair added somewhat to the properties of the material and did not degrade the fatigue of the substrate. However, a repair carried out under high spark energy conditions (to achieve a higher deposition rate) did create a fatigue debit below that of the unrepaired material. Thus repairs of fatigue-critical components should not be done under high energy conditions.
- *Corrosion (ASTM B117 salt fog, 168-hr ASTM G48 pitting and crevice corrosion).* There was no evidence of corrosion in salt fog testing. In the G48 tests, there was minor pitting in the ESD material but not in the substrate, presumably because of the presence of some porosity in the ESD material.
- *Wear (pin-on disk, and Hamilton-Sundstrand oscillating long stroke and fretting).* The ESD-repaired areas wore in essentially the same way as the substrate for dithering wear and about 30% less for long stroke wear. There was no evidence of different wear mechanisms or wear rates in the two materials.
- *Repair of chrome plating.* When repairing chrome damage in chrome plating, there is a tendency for the ESD repair to have a "halo" of porosity around the

repaired area. This problem was largely eliminated by depositing the ESD at low energy.

1.6 COST-BENEFIT ANALYSIS (CBA)

A cursory cost analysis was performed on the M1A1 gun cradle repair to determine the cost savings by implementing ESD for M1A1 cannon cradles. The cost to purchase a new component is $24,636. The reclamation costs have been determined to be $698.50, based on a labor rate of $76.50/hr for 9 hr and a material cost of $10. Annual savings for 15 items were thus estimated at about $360,000.

A detailed cost analysis was made of the following GTE items at OC-ALC: TF33 #5 bearing housing, TF39 compressor shaft, F100 10-12 stator segment. The cost-benefit for the bearing housing depended strongly on the number of lugs needing repair, with a 10-year net present value (NPV) of $1.3 million and a payback period of 4 months for an average repair of 6 lugs, but a 10-year NPV of -$1 million if an average of 12 lugs need repair. This demonstrates that the cost-effectiveness of the process is best when repairs are limited. The TF39 compressor shaft showed a 10-year NPV of $65,000 and a payback of 4 years. The F100 stator segment showed a 10-year NPV of -$24,000.

1.7 STAKEHOLDER AND END-USER ISSUES

ESD technology has demonstrated potential for repair of limited areas for dimensional restoration and salvage of components. With its low cost, simple manual operation, portability and low level of training, it is ideal for both depot- and operational-level repair. However, for engine components, which are some of the most sensitive flight-critical components that DoD overhauls, these characteristics are often disadvantages since they make it difficult to ensure process reproducibility.

ESD has already been adopted for some vehicle repairs at ANAD. In these cases there is obviously no issue of flight-criticality, and simple repairs can be used to reclaim a variety of expensive or difficult-to-obtain components. It is likely to find additional applications driven by ease of repair, cost-benefit, and the simplicity of developing repairs at the depot level without recourse to extensive engineering and laboratory facilities.

While the tests at NSWCCD were not as positive, it appears that, with further development and optimization, there is significant potential for the process for depot-level and perhaps even O-level in-place repair of components such as diving rods, shafts, and other components that suffer pitting corrosion. In order to find applications in this area, however, the process must be developed to the point where the quality of the repairs on Monels is similar to that seen in Inconels, especially in terms of the adhesion and porosity of the repaired area and its resistance to crevice corrosion.

For aircraft engines the cost of qualifying a repair and instituting the necessary TO changes is so high that, for it to be worthwhile, the cost-benefit must be clearly demonstrated before embarking on the effort. The easiest way to gain acceptance and adoption of the technology for

Air Force GTE repair is through the Materials Review Board (MRB) system, which is used whenever a component cannot be repaired by standard TO methods and an MRB engineer reviews the problem to determine whether the component must be condemned. In order to use ESD, MRB engineers must be aware of the capability of the technology, and see it as a method they can draw on for repairs where there are no other qualified repairs already specified in the TO. This is a matter of education and availability of the technology at the repair depot.

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2.0 TECHNOLOGY DESCRIPTION

2.1 PROCESS DESCRIPTION

2.1.1 General Technology Description

Electrospark deposition (ESD) is a microwelding technique with demonstrated capability for filling damaged areas and restoring coating damage. It is a pulsed-arc microwelding process that uses short-duration, high-current electrical pulses to weld a consumable electrode material to a metallic substrate. Microvolumes of electrode material are melted in the arc plasma of a pulsed current (spark) and fused into the substrate surface forming a metallurgical bond. Over time, many such electrode volumes, or splats, are overlapped on each other to provide a full coverage of new surface material. With additional overlapping passes, the new surface deposition material can build up more and more thickness. Electrode materials may be nearly any electrically conductive metal or ceramic/metal (cermet) mixture capable of being melted in an electric arc.

The ESD process is distinguished from other arc welding processes in that the spark duration is limited to a few microseconds and the spark frequency to approximately 1,000 cycles-per-second (Hz) or less. Thus, welding heat is generated during less than 1% of a weld cycle, while heat is dissipated during 99% of the cycle. This provides extremely rapid solidification, resulting in a nanocrystalline structure or, in some cases, an amorphous surface layer. Regardless of the structure that is obtained, the coatings are extremely dense and metallurgically bonded to the substrate. The combination of extremely fine grain structure, high density, and high bond strength offer the possibility of achieving substantial corrosion resistance, augmented wear resistance, and enhanced ductility. The low heat input eliminates thermal distortion or changes in metallurgical structure and thus allows the process to be used on heat-sensitive materials. Substrates require no special surface preparation and often no post-weld processes such as heat treatments. ESD is also advantageous from an environmental and worker safety standpoint. Best manufacturing practice generally recommends that in most applications a simple shroud with vapor exhaust be used to remove any fumes. Advanced Surfaces and Processes, Inc. (ASAP) conducted a study in which air samples were collected in the vicinity of the operator for ESD of aluminum onto cadmium plate in which an exhaust shroud was used. The concentration of cadmium was well below the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) [1].

In addition to using ESD for filling damaged areas, ESD has been implemented in many applications as a coating. The ESD coatings have been found to be very damage-resistant and are particularly suitable for use in severe environments involving high stresses, high temperatures, thermal cycling, irradiation, wear, corrosion, and erosion.

2.1.2 Equipment

ESD equipment consists of two major components; a pulsed, capacitor discharge; a power supply; and an applicator head (sometimes called a torch) with an electrical ground cable attached to the work piece to complete the electrical circuit between the electrode and the substrate. The process parameters controlled by the power supply include voltage, capacitance,

welding current, and pulse frequency. The power supply controls the wave form shape and the electrode motion.

The electrode is held and controlled by the applicator head and consists of a collet system for holding various sizes of electrodes; a conductor for supplying the pulsed welding current; a motor for providing rotational and/or oscillatory motion to the electrode, and an insulating sleeve for electrical and heat protection for the operator. The torch manufactured by ASAP has a water cooling system to allow for a 100% duty cycle.

A critical factor in ESD operation, as in conventional electric arc welding, is the need to break the contact between the electrode and the substrate. Without some type of relative motion, the electrode will weld itself to the substrate. Relative motion may be accomplished in a number of ways. Some torches rotate the electrode, others oscillate the electrode, and still others vibrate the electrode (in the axis of the electrode). Each of these torch configurations is available to provide a desired electrode motion effect.

Some ESD torches have an inert gas supply system attached to allow a protective cover gas, such as argon or helium, to flow onto the weld site at all times. The use of a cover gas provides protection from oxidation, furnishes cooling, and influences the physical properties of the arc, thereby affecting the characteristics of the deposit. For example, argon helps provide a smoother deposit and reduce oxide formation with some materials.

The ESD power supply and applicator head containing the electrode, manufactured by ASAP, are shown in Figure and Figure 1, respectively.

Figure 1. ESD Power Supply.

Figure 1. ESD Applicator Head (Torch).

Both mechanical and electrical parameters must be controlled in the ESD process. Mechanical parameters are very important for producing quality deposits and include travel motion of the electrode across the substrate, rotation (or oscillation) velocity of the electrode, step-over of the electrode with each pass to allow some overlap of deposit, and electrode contact force against the

substrate. Electrical parameters are also important for producing quality deposits and are equally significant for avoiding heat damage to the substrate. Electrical parameters include spark voltage, capacitance, pulse frequency, pulse duration (wave form width), pulse current, and circuit inductance. Spark energy, or heat to the substrate, is affected by the voltage, current, and capacitance. Higher voltages and currents produce higher spark energy and a resulting increase in deposition rate and roughness. Larger capacitance produces a wider pulse width and thus can put more heat into the substrate. If heating of the substrate must be avoided, the ESD should be done with lower total energy values.

2.2 TECHNOLOGY DEVELOPMENT AND APPLICATION

There are many types of applications for which ESD can be used as a surface engineering process, primarily because of the wide variety of materials that may be deposited. Nearly all electrically conducting materials with a melting point may be considered for both electrodes and substrates. Surface properties of metallic substrates can therefore be modified to produce a very large number of desired properties.

Two major types of applications receive ESD treatments—surface modification and buildup repair. Most surface modification applications involve enhancement of tribological properties of surfaces. Commonly used electrodes for wear and friction enhancement include sintered carbides, borides, and hard alloys such as Stellite 1, Stellite 6, Tribaloy 700 and 800, and molybdenum. The dynamic coefficient of friction of machine component surfaces can be reduced from 0.6 to less than 0.2 with an ASAP proprietary process. Corrosion applications frequently are addressed with iron-aluminide and nickel alloys such as Inconel 625 alloy (IN625) and Hastelloy C-22.

Wear applications commonly treated with ESD include cutting edges of chipper knives, saw teeth, and mower blades; wear surfaces of slurry pumps, dewatering drums, water treatment valves, and food processing dies; and grip surfaces of dental extraction forceps, surgical hemostats, and needle holders.

Using ESD to make relatively thick deposits for defect repair and dimensional restoration has become more prevalent in the last several years. Most very hard materials, such as carbides, cannot be deposited more than a few thousandths of an inch without stress-induced cracking. But more ductile alloys can be deposited to any desired thickness and therefore can be used for repair or restoration. Applications for ESD repair include components of steel, stainless steel, nickel- and cobalt-based superalloys, aluminum, Monel, titanium, and magnesium. Examples of such components are turbine blades and vanes, shaft seals, bearing housings, actuator rods, and hydraulic cylinders in aircraft, aircraft engines, military vehicles, and submarines. Illustrative examples are shown in Figure 2.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

The following government-sponsored projects relate to investigating properties of ESD coatings or developing ESD applications. Additional information can be obtained by contacting ASAP.

Strategic Environmental Research and Development Program (SERDP) Project. ESD Tungsten Carbide and Co-Based Alloy Coatings for Replacement of Electrolytic Hard Chrome [2]. The objective of this project was to develop and demonstrate a controllable non-line-of-sight (NLOS) process for coatings to replace electrolytic hard chrome (EHC) on military components whose geometry does not allow the use of present alternative processes such as high velocity oxy-fuel (HVOF) coatings. ESD operating parameters for coating 4340 steel with tungsten-carbide/cobalt cermet materials were optimized, and several tests were performed on optimum coatings, with results compared to those for EHC plated on 4340 steel. These tests included: metallography, particle erosion wear, sliding wear, and salt-fog corrosion. ASAP worked with Roger Johnson at Pacific Northwest National Laboratory, and the findings were published in the Final Report for the SERDP project.

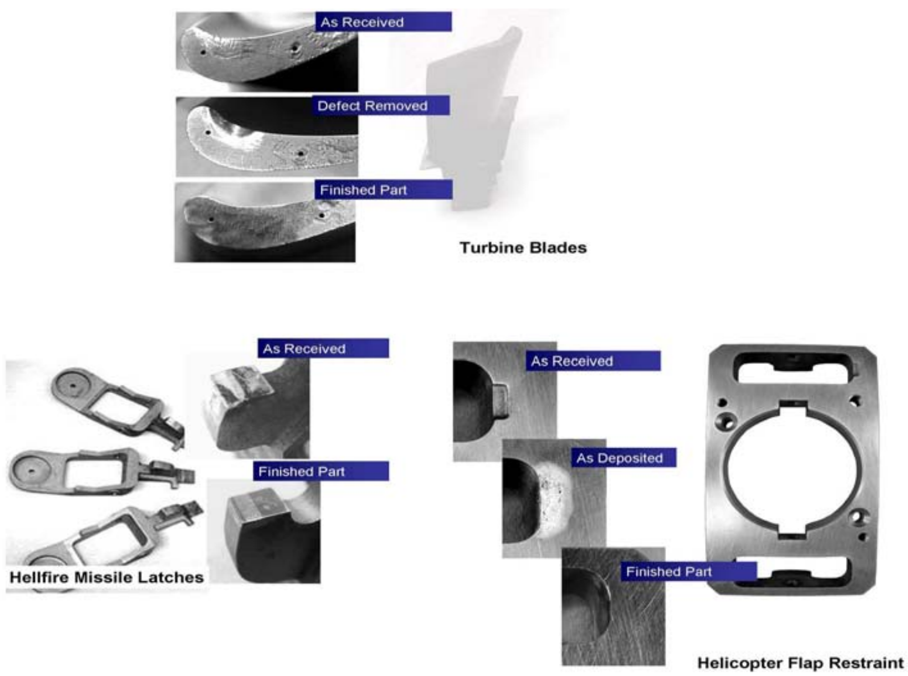

Figure 2. ESD Applications for Defect Repair and Dimensional Restoration.

Small Business Innovation Research (SBIR) Project. Repair of Corrosion Coatings of Cadmium Plating and IVD-Aluminum with ESD [3]. The objective of this project was to explore the feasibility of making repairs of cadmium plating and ion-vapor-deposited aluminum on steel substrates with the ESD process. The project involved the evaluation of ESD-aluminum deposits and applications for repair as well as the ESD applications of cadmium. Since the welding of (or with) cadmium metal may generate toxic vapors and respirable particles, the processes were performed with protective and automated equipment to prevent human exposure.

Army Armament Research and Development Engineering Center (ARDEC) Project. ESD Coating ID of Gun Barrels [4]. The M249 semiautomatic weapon currently employs chrome plating to enhance barrel life. The project investigated the viability of using the ESD process as a replacement for chrome plate. ESD was applied to the interior surface of M249 barrels with a semiautomated, non-line-of-sight process.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.4.1 Advantages

The ESD process generally uses a pulsed current of a few hundred Hz pulse rate and a very narrow pulse width to provide low heat input to the substrate while depositing microvolumes of electrode material. The low heat input results in five of the major benefits of the ESD process - a minimal heat affected zone (HAZ); minimal annealing effect in the substrate; and very little dilution, minimal residual stress, and low distortion when compared to conventional welding methods. As a result of these benefits, some alloys normally considered to be "unweldable" due to cracking in the deposit and substrate can be successfully repaired or built up with ESD. Another benefit of the process is the metallurgical bond between the ESD deposit and the substrate. This very strong bond prevents ESD deposits from chipping or spalling. The rapid solidification of ESD deposits frequently results in enhanced properties, such as increased hardness, increased wear and corrosion resistance, and a reduced friction coefficient. These effects are undoubtedly due to a very fine grain structure formed during rapid quenching, a phenomenon called the Hall-Petch Effect. Grain sizes of 100 nanometers or less are not uncommon, and some materials can actually solidify to an amorphous state.

The ESD process is environmentally benign, easily automated, and generally requires no pre- or post-treatments (masking/thermal treatment). No toxic waste streams are produced. Because the equipment is relatively small, it is field portable and can easily be used for many in situ applications. Another distinct advantage of the ESD process over other welding or coating processes is its ability to make coatings and repairs in non-line-of-sight applications.

2.4.2 Limitations

Because very small volumes of electrode material are transferred with each electrical pulse, the deposition rate is low, especially compared to batch processes such as electroplating or automated thermal spray processes. Therefore, the trade-off of benefits versus cost to produce must be made.

The deposition of ESD material typically produces a textured surface with an average surface roughness of greater than 100 microinches. Applications requiring a fine surface finish may not be good candidates for the ESD process. However, if the ESD deposit is thick enough, fine abrasive grinding or super-finishing can remove the as-deposited surface roughness and produce a finish in the 8- to 16-microinch range, depending on the material being deposited.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The objective of this project was to qualify ESD as technically feasible and economically viable for the repair of different types of weapons systems components. Because of the Propulsion Environmental Working Group's (PEWG) participation and the Air Force Materiel Command's financial support, it was decided that the main focus of the project would be on gas turbine engine (GTE) components. A complete Demonstration Plan Electrospark Deposition for Localized Repair of Gas Turbine Engine Components [5] was developed in accordance with requirements of the Environmental Security Technology Certification Program (ESTCP) for the validation of the ESD process. Incorporated into the Demonstration Plan was a joint test protocol (JTP) that covered the materials testing of the ESD process related to GTE components. The JTP was produced through meetings and electronic communication involving all the stakeholders and delineated all the materials testing required to qualify ESD for a production-scale process. The stakeholders included Department of Defense (DoD) GTE repair facilities and GTE original equipment manufacturers (OEM).

Prior to the execution of the JTP, the ESD process was optimized, and the information gathered in the optimization process was used in preparing the mechanical test specimens for the JTP. Optimization also included the selection of materials (substrates, electrodes, and non-ESD coatings), metallurgical evaluation, and some mechanical testing. The results of optimizing the ESD process are summarized below.

Using the optimum ESD parameters and techniques, mechanical test specimens were prepared and additional material data was generated in accordance with the JTP. This data was crucial in determining the ESD repair procedures for potential GTE components. The key aspect to demonstrating the viability of the ESD process was fabricating test specimens with known defects, repairing the defects using ESD, and then demonstrating that the properties of the repaired material were comparable to the original material, or at least met the acceptance criteria. In addition to materials testing, demonstration of the ESD process for repair of selected GTE components was part of this effort and the results of those demonstrations are presented below. Table 1 lists the performance objectives from the Demonstration Plan and indicates whether the performance objectives were met.

3.2 SELECTION OF TEST FACILITY

Oklahoma City Air Logistics Center (OC-ALC) was the lead demonstration repair facility for demonstration of the ESD process for repair of GTE components. Early in the project, the PEWG acquired an ESD unit from ASAP and had it installed at the Air Logistics Center (ALC). ASAP technical experts performed training of ALC personnel in the operation and maintenance of the ESD equipment.

3.3 TEST FACILITY HISTORY/CHARACTERISTICS

In 1942 Tinker Field was established near Oklahoma City, and its industrial plant repaired B17 and B24 bombers and engines, and fitted B29s for combat. In 1946, Tinker expanded to include

the Douglas Aircraft Plant and was named Oklahoma City Air Materiel Area. In the 1950s, it expanded to include overhaul of the B52 bomber and the KC135 tanker. In 1974, the depot was renamed the Oklahoma City Air Logistics Center.

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Where Assessed	Actual Performance Objective Met?
Quantitative	Deposition rate	Ability to deposit alloy material (such as Inconel 718) at a rate in excess of 3 mg/min (actual arc time) with the quality of the coatings such that they pass the acceptance criteria specified in the JTP	OP*	Yes
Quantitative	Surface finish	Ability to hand sand and blend ESD-repaired area to match surface finish of adjacent area	OP, JTP	Yes
Qualitative	Microstructure	Microstructure includes items such as grain size, inclusions, and mixed phases. Microstructure of ESD-repaired area should generally be similar to base material (per American Society for Testing and Materials [ASTM] E3).	OP	Generally, Yes
Quantitative	Discontinuities	Porosity of ESD repair should be less than 2% with no large voids.	OP, JTP	After optimization, Yes
Quantitative	Microhardness	In general, microhardness of ESD-repaired area should be within ±20% of base material (per ASTM B578)	OP, JTP	Yes
Quantitative	Fatigue	Because ESD repair generally has tensile residual stresses, some fatigue debit is anticipated. Amount of allowable debit depends on application but generally should be no worse than encountered with hard chrome plating (per ASTM E466).	JTP	Yes
Quantitative	Tensile	Tensile, yield strength and ductility of ESD-repaired area should be no lower than that of base material (per ASTM E8).	JTP	Yes
Quantitative	Wear	Sliding and abrasive wear rates of ESD-repaired area should be equal to or less than those for base material.	OP, JTP	Yes
Quantitative	Corrosion	In salt-fog or atmospheric corrosion tests, time until observing corrosion product for ESD-repaired area should be less than or equal to time for base material (per ASTM B117). Open-circuit potential for ESD area and base material should be equal.	JTP	Yes
Qualitative	Bond strength	Bond strength of ESD-repaired area should exceed that of adhesive used (per ASTM C633).	JTP	Yes
Qualitative	Depot repair capability	Ability to repair components with typical localized damage found on engine parts at OC-ALC, including ability to restore dimensions without deleterious wear or corrosion properties	Component demo	Yes
Qualitative	In-place repair	Ability to repair some components in place without removal from weapons system, with performance equivalent to adjacent nonrepaired area	Component demo	Not completed

*optimization procedure

The ALC industrial complex has 55 buildings with 5.5 million sq ft and plant equipment valued at more than $500 million. The maintenance work force consists of more than 6,100 and the payroll more than $300 million. The center manages approximately 82,000 accessory items and annually repairs approximately 250,000 exchangeable components.

OC-ALC manages 19 types of engines (aircraft jet engines, missile engines, and helicopter engines). It is designated the source of repair (SOR) for 11 of the 19 and is currently repairing the TF30, TF33, F101, F108, F110, and F118 engines. The center also is the SOR for the Navy F110-400 and TF30-414A engines and manages the J79 engine. Within the Air Force, there are approximately 18,500 active engines, and in FY2004, OC-ALC overhauled 975 engines.

During overhaul a number of components must be repaired due to wear, gouges, or corrosion pits. For items that can be repaired, EHC plating is often used subsequent to machining of the damaged area. As examples, on the TF33 engine there are 12 separate components and on the F100, 41 separate components that are commonly plated with hard chrome. In FY2004, there were approximately 700 TF33 components onto which EHC was applied during repair operations. In many cases, the damage is localized to specific regions on the GTE components, and repair using ESD in just those areas as opposed to large-scale machining and application of EHC plating would save time and reduce costs. There are also many components for which there currently is no repair and for which ESD might be a viable option for reclaiming the components and saving the cost of acquiring replacement components.

3.4 PHYSICAL SET-UP AND OPERATION

As discussed in Section 2.1, the ESD equipment is very portable and can be located anywhere in a repair facility as long as there is electrical power. A complete ESD unit was acquired and delivered to OC-ALC where it was setup in a location where surface finishing operations are conducted on GTE components. Figure 4 shows the ESD equipment at OC-ALC that was used for demonstrating repairs on GTE components. Figure 5 shows application of a coating to a test coupon at OC-ALC.

Figure 4. ESD Equipment Located at OC-ALC.

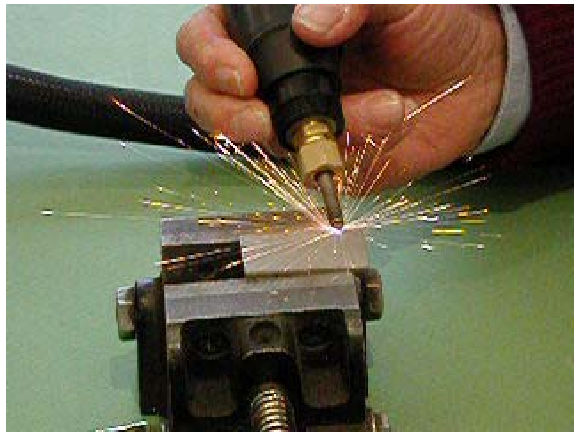


Figure 5. Application of ESD Coating to Test Coupon at OC-ALC.

3.5 ENHANCEMENT OF ESD PROCESS

The ESD process is usually performed using a handheld electrode holder assembly. The manual ESD method allows flexibility, and the coatings are easily applied. However, automation of the ESD process has proven in previous testing to result in higher quality and more consistent deposited material when compared to a manual application. Automation, operating all day with little human intervention, demonstrates an increase in repair production rates and is essential in situations where enclosed chambers are required, either for a desired atmosphere (i.e. 100% argon) or environmentally hazardous applications (i.e., repair of cadmium plating). Automation is also critical in non-line-of-sight applications where a handheld method is not possible or practical.

ASAP has performed extensive research in improving the quality of ESD using a variety of automated systems. However, the maximum thickness of an ESD deposit appears to be limited due to the formation of a nonuniform (bumpy) surface after a certain number of passes. The nature of ESD tends to accentuate surface geometry, which can lead to low quality deposits, specifically the formation of bridging porosity. If the ESD surface could remain smooth and uniform between passes, the thickness of an ESD deposit may be unlimited. It was believed that incorporating ultrasonic impacting equipment in conjunction with the automated ESD equipment could achieve this type of surface.

Ultrasonic impact treatment (UIT) is based on the conversion of harmonic oscillations of an acoustically tuned body into resonant impulses of ultrasonic frequency. The energy generated from these high frequency impulses is imparted to the treated surface through the contact of specially designed pins. These transfer pins are free to move axially between the resonant body and the treated surface. To couple the ultrasonic generator to the treated surface, the pins are impacted upon the surface causing a local plastic deformation similar in appearance to peening. This results in a visibly smoother surface than that of as-deposited ESD. While the primary focus of this investigation was using UIT equipment to improve surface finish, the effect of the ultrasonic energy imparted by UIT was also measured. This energy penetrates much deeper than the energy attributable to the peening aspect of its application and can be tuned to induce compressive stresses in the substrate to a depth of up to several millimeters.

The objective of this portion of the project was for ASAP, working in conjunction with Portland State University (PSU), to demonstrate improvement in quality and production rates of ESD deposition on Inconel 718 alloy (IN718) through automation and UIT. This effort was in support of the objective of identifying ESD repairs for GTE components and was completed in two phases. The results of the first phase were very promising, which led to a second phase of additional investigation and refinement.

Details of the results of the automation and UIT studies are provided in the Final Report [2] and are only summarized here. For automation, the ESD torch was connected to the end of a Motoman robotic arm with 6° of freedom through a pneumatic load control system, which was used to control the amount of downward force of the electrode tip to the substrate while applying an ESD coating. UIT operation consists of manually moving the UIT gun containing the pin over the area where an ESD coating is being applied. The gun must be held so that the impacting pin is perpendicular to the surface being treated. During Phase I of this project, this was done manually but for Phase II a semiautomated fixturing system was employed. Two different pin diameters were used in Phase I of this project, 0.125 in and 0.25 in tool steel pins. In Phase II the steel pins were replaced with 0.25 in diameter tungsten carbide pins. One was slightly rounded and the other was flat. Figure 6 shows the UIT treatment involving impact of a 0.25 in diameter pin on the surface of a metal plate.

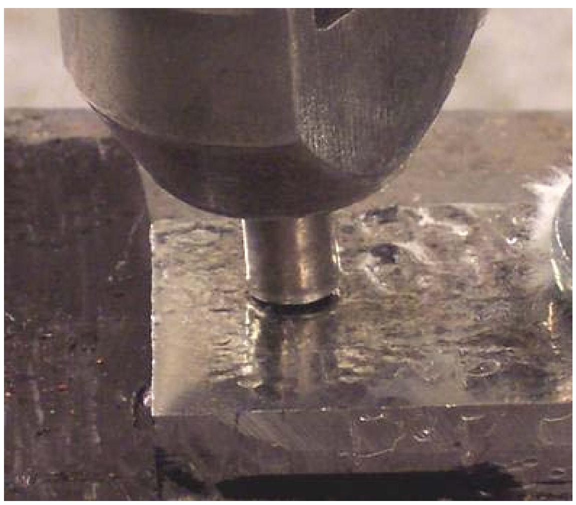


Figure 6. UIT Treatment Process Using a 0.25-in Diameter Pin.

Figure 7 summarizes how the application of automation and UIT increased the effective deposition rate and decreased the porosity (discontinuities) in the ESD coatings. In general, through the use of these techniques, the deposition rate could be increased by about an order of magnitude and the porosity decreased by about a factor of three.

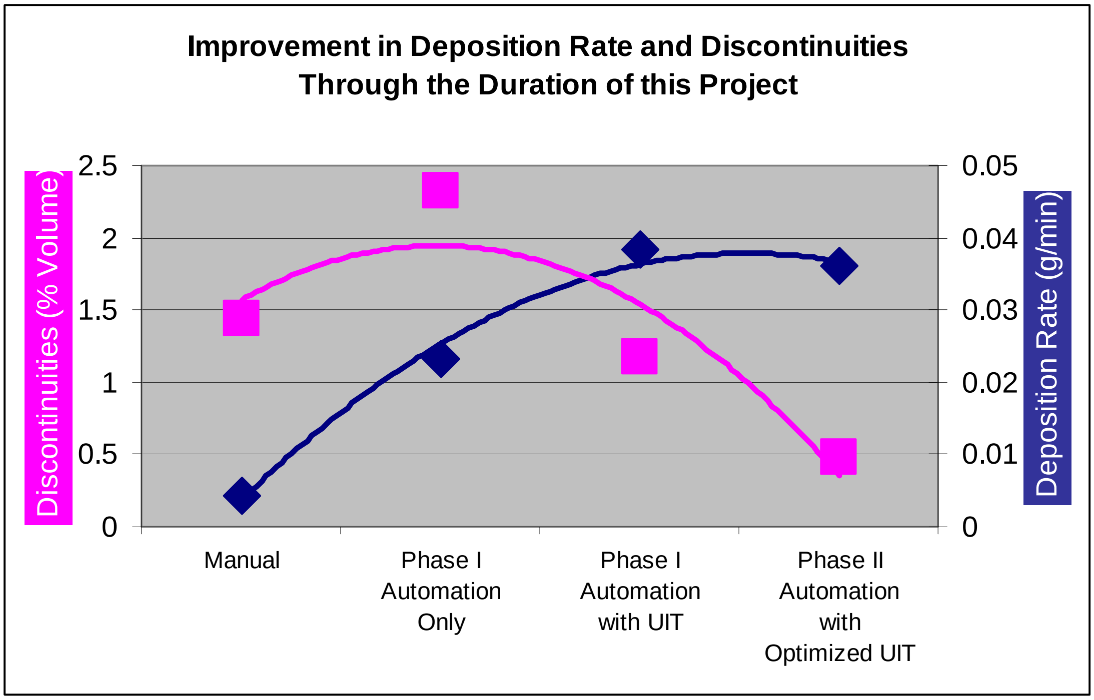


Figure 7. Deposition Rates and Porosity (discontinuities) **for Manual Deposition of IN718 and for Use of Automation and a Combination of Automation with UIT.**

3.6 ANALYTICAL METHODS

For execution of the JTP, because of its primary importance to OC-ALC, IN718 was used as the base material and the ESD deposition material for executing the tests delineated in the JTP. The objective of this work was to demonstrate that ESD could be used to repair localized damage such as wear scars and corrosion pits on GTE components so, in order to perform materials tests that would demonstrate this capability, it was necessary to develop and define "standardized" defects in test coupons. Table 2 describes the defect geometries that were developed. Each defect was designated with a specific type number. The purpose of selecting these geometries was to assess repairability and reproducibility in typical repair situations.

Table 2. Defect Geometries.

Groove type	Dimensions	Applications
Type 1	0.25 in diameter, 0.020 in deep	Point repair
Type 1a	0.10 in diameter, 0.006 in deep	Point repair of non-ESD coating, not penetrating substrate
Type 1b	0.15 in diameter, 0.014 in deep	For tensile and fatigue tests
Type 2	0.375 in wide, 0.020 in deep, axial groove	For Hamilton Sundstrand wear test

The deposition of the IN718 coatings was optimized using a design-of-experiment (DOE) approach. The inputs to the DOE were the ESD parameters, namely pulse rate, voltage, capacitance, electrode revolution speed and electrode size. The DOE outputs were deposition rate, microhardness and porosity. As a result of the DOE, two parameter sets were selected, with

one designated V4 that had a high deposition rate and moderate overall quality and the other designated #32 that had a medium deposition rate and excellent quality based on porosity and microhardness. Table 3 lists the parameters for each designation.

Table 3. Parameters Selected for Mechanical Test Specimens.

Coupon Number	Pulse Rate (Hz)	Voltage (V)	Capacitance (μF)	Electrode Size (mm)	Electrode Speed (rpm)	Current (A)
V4	400	180	50	2.4	1,200	7
#32	400	105	50	3.2	1,200	4

The materials test methods and procedures were described in detail in the Demonstration Plan [5] and are only summarized here.

Fatigue

The purpose of fatigue testing was to evaluate the effect of ESD on the fatigue properties of the underlying material. Since there are several different types of fatigue tests, it was essential to define the one that best represented the conditions that a GTE component would encounter in service. For most ESD testing to-date, axial fatigue testing (ASTM E466) provided the most useful data for evaluation. The need for low-cycle-fatigue (LCF) testing in GTE applications is driven by design consideration for the number of engine take-off/landing cycles. Therefore, only LCF testing was conducted. Because of the types of stresses encountered by most GTE components, the fatigue test specimens in this project were subjected to tensile stresses only.

The test specimens were fabricated from IN718 with flat plate geometry and a constant gage width. The defect was a small divot in the center of the gage length to allow the evaluation of the effect an ESD deposit has on the fatigue life of the substrate. The specimens were used to provide full stress versus number-of-cycles (S-N) curves to determine fatigue life and fatigue initiation locations. Some specimens had a Type 1b defect at the center of the gage section that was filled via ESD and machined back to specification. Others had a defect without an ESD fill. Still others had no defect but an ESD overlay (bead-on-plate). Baseline data was established on specimens with and without a defect and without ESD. Figure 8 shows a photograph of fatigue specimens with and without the defect.

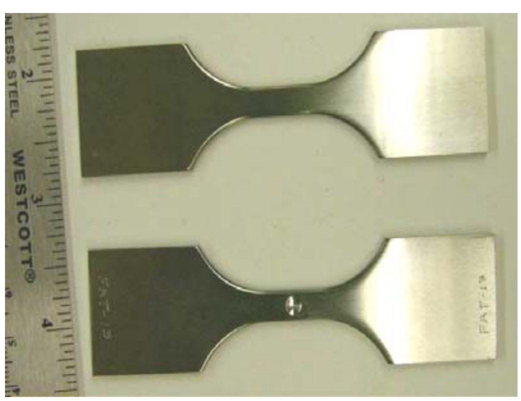


Figure 8. IN718 Fatigue Specimens Without (top) **and With** (Bottom) **the Type 1b Defect.**

Fatigue testing consisted of repeated load application in tension-tension (the applied load never reached zero or compression) with a load ratio (minimum load/maximum load) (R-ratio) of 0.05. The number of load cycles was counted until the specimen broke. The cycles and location of fracture were recorded. The data was plotted on a semi-log plot of maximum applied stress (load/specimen cross sectional area) versus cycles to failure. This format is a standard S-N fatigue curve.

Tensile Testing

The purpose of tensile testing was to evaluate the effect of ESD on the tensile properties of the underlying material (yield strength, ultimate (tensile) strength, elongation, and area reduction). The specimens used were identical to those used for the fatigue studies, including some with the Type 1b defect.

The tensile test was conducted in accordance with ASTM E8, a standard method of tension testing of metallic materials to determine the yield strength, yield point, ultimate (tensile) strength, elongation, and area reduction of a specimen. Testing was conducted in laboratory air at room temperature. Standard stress-strain curves were generated for the resulting test data. Failure analysis of the specimens was performed.

Wear—Pin-on-Disk

The pin-on-disk wear test was basically used as a screening test to demonstrate that an ESD repair of a defect in a disk could restore a surface to a point such that there would be no difference between virgin and repaired material in sliding wear. The disk was fabricated from IN718 and had a diameter of 1.9 in and a thickness of 0.125 in. Three Type 1 defects were machined into one face of the disk and then repaired using ESD as shown in Figure 9. The pins were 0.125-in-diameter 52100 steel balls with a hardness of Rockwell C 58.

Figure 9. Pin-on-Disk Wear Test Specimen After Defects Repaired Using ESD but Prior to Surface Finishing.

The tests were conducted in accordance with ASTM G99, with a load of 138 grams on the pin and the friction force being measured using a force transducer. No lubricant was used. Wear on the disk was measured by surface profilometry.

Wear—Sliding and Fretting

The purpose of these tests was to quantify the wear rate between virgin IN718 (baseline) and ESD repaired IN718 under both long (sliding) and short (fretting or dither) stroke conditions. The fretting wear test was selected to simulate the dithering or vibration movement between two mating components that are typical in GTEs. It was believed that there were no standard ASTM wear tests that would accurately reflect conditions of use for GTE components, so a wear test designed by Hamilton Sundstrand (H-S) and using their apparatus was selected.

Wear test plates fabricated from IN718 of size 1.5 in x 8 in x 0.25 in-thick had four Type 2 defects machined into them, as shown in Figure 10. These were subsequently filled using ESD and surface-finished to the same level of roughness as the remainder of the plate. Four IN718 counterface specimens of size 2 in x 0.25 in x 0.125 in-thick were used in each test.

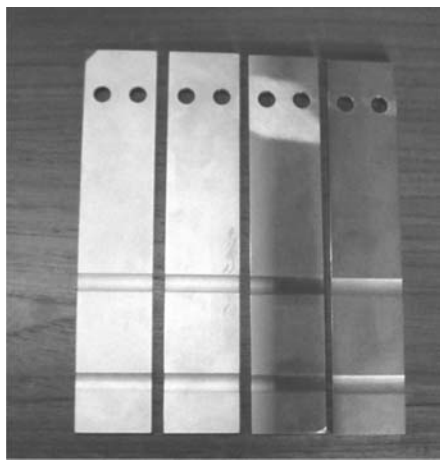


Figure 10. Sliding/Fretting Wear Test Plates Showing Type 2 Defects (grooves).

The wear testing was performed by United Technologies Research Center (UTRC). One test plate was held in a fixture that used a screw driven lever arrangement to apply a fixed load to the four counterface specimens. Relative motion between the plate and counterface specimens was provided by a standard tensile test frame (see Figure 11). The fixture design allowed four repaired areas to be tested simultaneously with each test panel. Loads were chosen to obtain visible wear on the specimens. Wear tests were performed without lubrication. Ten plates were evaluated, with six containing ESD-repaired defects and four virgin plates. A load of 150 lb was applied to the counterface specimens against the plate. The long stroke wear test consisted of cycling the plate at ± 0.10 in at 1.5 Hz for 100,000 cycles. The dithering wear consisted of cycling the plate at ± 0.010 in at 15 Hz for 1,000,000 cycles. Photographs, dimensional measurements, and weight measurements were taken for all plates and counterface specimens before and after each test.

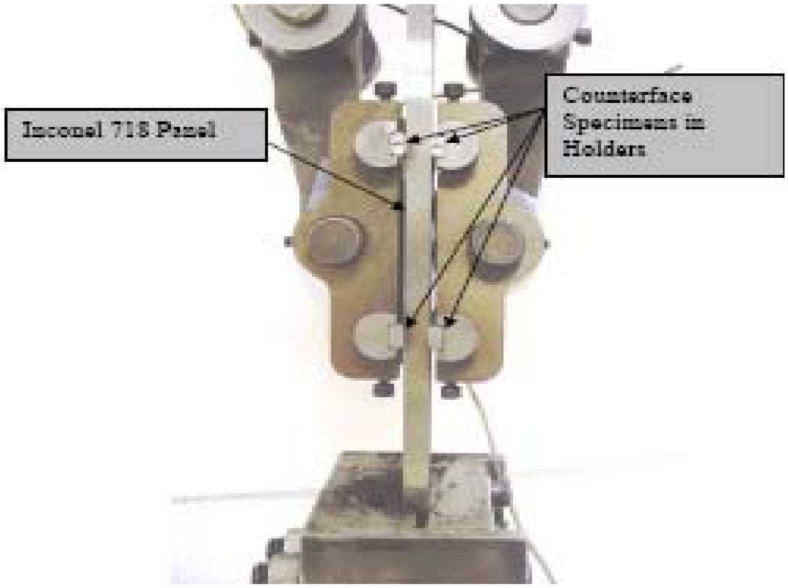


Figure 11. Photograph of Sliding/Fretting Wear Test Apparatus Showing Plate with Four Counterface Specimens.

Corrosion

Corrosion testing was performed to determine if material deposited using ESD was more susceptible to corrosion than the base material. For these studies, IN718 1 in-diameter flat specimens with Type 1 defects in the center of one face were used. The defects were filled using ESD, with UIT used on some, and then the surface was ground to ensure that it was flush with the rest of the specimen.

Two types of corrosion tests were performed. The first was the ASTM B117 salt fog test, in which the specimens were exposed to a 5% salt fog at 35º C for 168 hrs, with an assessment performed at 24-hr increments. The second was a pitting and crevice corrosion test performed in accordance with ASTM G-48.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

The performance criteria for all the materials testing were delineated in Section 3.1. For all materials testing but fatigue, the essential criterion was that the performance of the ESD "repair" of the defect induced in the specimen had to be equivalent to the virgin material. For fatigue, the ESD process could not induce a fatigue debit, and the ESD "repair" had to restore at least some of the fatigue strength. For repair of components, the ESD process had to restore the component to its original dimensions, and the performance had to be equivalent to that of a non-damaged component. Table 4 shows the expected performance and performance confirmation methods taken from the Demonstration Plan [5] and the actual performance.

Table 4. Expected Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Method	Actual Performance (post demo)
PRIMARY CRITERIA (Performance Objectives, Quantitative)			
Hazardous Materials			
Reduce chrome plating	Reduction in use of hard chrome plating through application of ESD for localized repair of noncoated components or chrome plating already on components	Mass balance	Use of ESD to repair chrome plating restricted to select cases
Factors Affecting Technology Performance			
Equipment parameters and operator techniques	To be optimized in the execution of the JTP. Performance will depend on service conditions for each type of component repaired. In general, the repair is not expected to affect performance negatively in terms of fatigue, wear, or corrosion but should increase the total life of the component, reduce frequency of component condemnation, and thereby reduce life-cycle costs.	Measure performance of ESD repairs in terms of fatigue, wear, and corrosion	ESD repairs generally acceptable in terms of fatigue, wear, and corrosion
Ease of Use			
Manpower	One artisan skilled in electrospark deposition will be required to operate the process; several extra operators are needed for startup.	Operating experience	Demonstrated
Skill	The artisan will need training (estimated at several weeks) specifically related to electrospark deposition, including knowledge of material safety data sheet (MSDS) for materials being deposited and process procedures. Use of Analytical laboratory will be required.	Operating experience	Demonstrated
Monitoring	Deposition parameters must be monitored and recorded during all ESD depositions	Operating experience, recordkeeping	Demonstrated

Table 4. Expected Performance and Performance Confirmation Methods (continued).

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Method	Actual Performance (post demo)
SECONDARY PERFORMANCE CRITERIA (Qualitative)			
Ease of Use (continued)			
OSHA training	OSHA health training related to potential vapors emitted by process and safety training related to high-voltage / high-current equipment will be necessary.	Recordkeeping	Demonstrated
Shift	Equipment may be operated either one shift per day or 24 hrs per day.	Operating experience	24-hr-per-day operation not demonstrated but capability exists
Product Testing			
Microstructure/ Macrostructure	An acceptable microstructure and macro-structure must be defined and will be dependent on the requirements of each component. The accepted microstructure will be compared to alternative processes such as thermal spray, plasma spray, and electroplate coatings.	ASTM E 3.	Acceptable microstructure achieved
Residual stress analysis	Only enough specimens will be tested to obtain an indication of the presence of residual stresses due to the ESD process.		Residual stresses slightly tensile
Bond strength	Only enough specimens will be tested to demonstrate that the ESD will not delaminate from the substrate.	ASTM C 633	Bond strength of ESD deposits excellent
Reliability			
ESD equipment	Equipment must be robust and reliable.	Recordkeeping	Demonstrated
Versatility			
Other applications	Equipment may be used for a variety of ESD applications and materials.	Operating experience	Demonstrated
Other locations	Equipment may be installed at any location.	Operating experience	Demonstrated
Scale-Up Constraints			
Ventilation	Adequate ventilation controls per the heath and safety regulations for fume and particle removal	Operating experience	Demonstrated
Cover gas delivery	Adequate delivery system to shield process, if necessary	Operating experience	Demonstrated

4.2 PERFORMANCE DATA

Fatigue

The cycles-to-failure at different stress levels were plotted for each of the six ESD conditions evaluated—baseline, baseline with defect, bead-on-plate, defect repaired using #32 ESD parameters, defect repaired using V4 ESD parameters, and defect repaired using #32 ESD parameters with UIT. Equations were determined using regression analysis that provided a best fit to the data points. The Final Report for the project [6] lists the exact cycles-to-failure for each specimen and provides the equations.

Figure 12 shows the data points and fitted curves for all six conditions. The results show that, as expected, introducing the defect into the specimens reduces the fatigue life. The bead-on-plate results show that the ESD application also reduces the fatigue life by about the same amount. Using the higher-deposition-rate V4 ESD parameters further reduces the life, with the slope of the #32 S-N curves being different, indicating that the fatigue life improves at the lower stress levels. The best results were obtained using the #32 parameters with UIT, with the fatigue life being virtually restored to the level obtained with the virgin specimens with no defect.

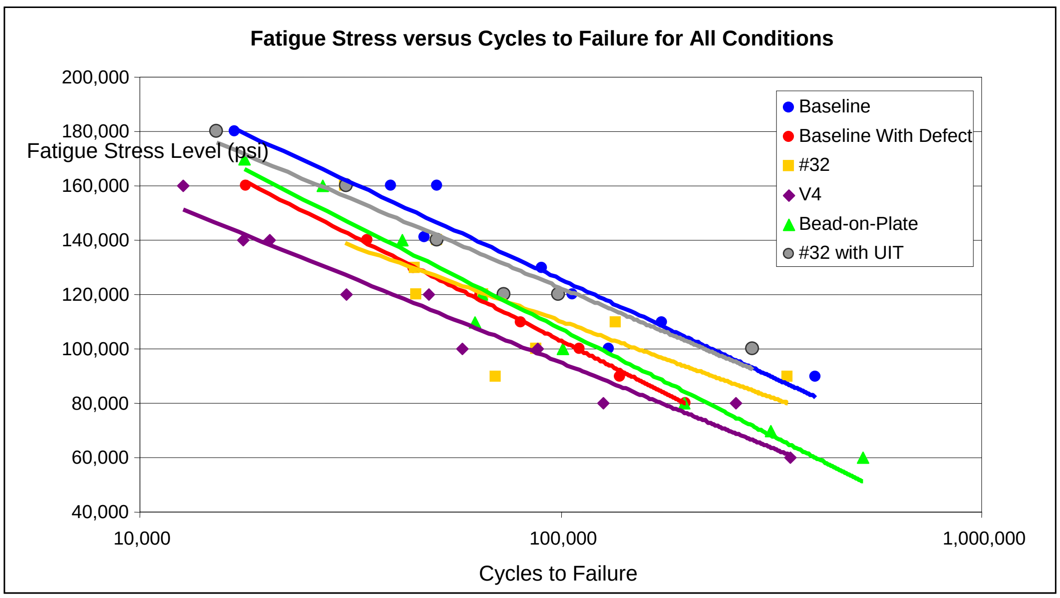


Figure 12. Cycles-to-Failure at Different Stress Levels for Six Specimen Conditions.

Tensile Testing

Stress-strain curves were obtained for each of the six specimen configurations. To obtain adequate statistics, six baseline specimens, six baseline specimens with defects and three specimens for each of the other configurations were tested. From those, the yield strength, ultimate tensile strength, and the reduction in area and elongation were determined. The results are summarized in Table 5. The average yield strength of all configurations was between 170

and 173 thousands of pounds per square inch (ksi), and the average ultimate tensile strength was between 196 and 198 ksi.

Table 5. Tensile Test Data Summary.

Specimen Configuration	Average Yield Strength (ksi)	Average Tensile Strength (ksi)	Average Reduction in Area (%)	Average Elongation (%)
Baseline	173.4	198.4	38.0	29.06
Baseline with defect	169.8	198.1	29.5	17.44
#32	171.6	196.8	27.3	20.53
V4	172.3	195.7	26.3	18.53
Bead-on-plate	171.6	197.5	36.7	26.20
#32 with UIT	169.8	196.2	26.7	19.49

All of the fractures occurred through the center of the gage section and the ESD material except for the bead-on-plate configuration, which tended to break at the edge of the ESD repair rather than at the center.

Wear—Pin-on-Disk

Most tests were run for 100 revolutions. To generate a deeper groove and extended friction data, a longer test was run on one specimen with a total of 2,000 revolutions, which produced a sliding distance of 650 ft. Friction coefficients, μ, averaged 0.25 on as-finished (ground) surfaces at the start of the tests. The friction steadily increased for approximately 50 revolutions, at which point the friction coefficient reached a steady-state value of 0.87. The pin/disk apparatus was unable to differentiate between the base metal and ESD repaired areas. For the longer test, the friction coefficient did not vary significantly over the 2,000 revolutions once steady-state had been achieved.

The maximum groove depth formed in the disk averaged 112 μin in the base metal and 124 μin in the ESD-repaired areas. The extended test produced maximum groove depths of 194 and 218 μin for the base metal and ESD-repaired areas, respectively. The maximum weight loss for both pins and disks was 0.3 grams with some items not losing or gaining weight. Because there was no consistency to weight gain or loss, no conclusions could be made of the relative performance of the ESD-repaired areas versus the base metal.

Wear—Sliding and Fretting

Ten IN718 specimens were prepared and tested, as indicated in the test matrices shown in Table 6 and Table 7. Subsequent to testing, all the panels and counterface specimens were weighed, and from that data a wear volume was calculated. The wear coefficients for the panels and counterface specimens were calculated using a modified Archard's equation:

$$K = \frac{Wear\_volume}{DxL}$$

where K, D and L represent the wear coefficient, total distance traveled, and the applied normal load, respectively. The wear coefficients for the sliding and fretting tests are shown graphically in Figure 13 and Figure 14.

Table 6. H-S Wear Test Matrix for IN718 on IN718.

Substrate Material	Specimen Number	Defect Type	ESD Material	Qty	ESD Parameters	Stroke Length
IN718	S1 and S12	none	none	2	Baseline	Short stroke (fretting)
IN718	S2 and S13	none	none	2	Baseline	Long stroke (sliding)
IN718	N5	Type 2	IN718	1	#32	Short stroke (fretting)
IN718	N3	Type 2	IN718	1	#32	Long stroke (sliding)
IN718	N2	Type 2	IN718	1	V4	Short stroke (fretting)
IN718	N6	Type 2	IN718	1	V4	Long stroke (sliding)
IN718	N1	Type 2	IN718	1	#32 with UIT	Short stroke (fretting)
IN718	N4	Type 2	IN718	1	#32 with UIT	Long stroke (sliding)
			Total	10		

Table 7. Test Parameters for Wear Test on IN718 Panels With and Without ESD Repair.

Wear Test Matrix for ESD-Applied IN718						
Test #	**Panel**	**Frequency (Hz)**	**Cycle**	**Displacement (in)**	**Clamping Load (lbf*)**	**ESD Repaired?**
1	S-1	15	1,000,000	0.01 to -0.01	150	No
2	S-2	1.5	100,000	0.1 to -0.1	150	No
3	S-12	15	1,000,000	0.01 to -0.01	150	No
4	S-13	1.5	100,000	0.1 to -0.1	150	No
5	N-1	15	1,000,000	0.01 to -0.01	150	Yes
6	N-4	1.5	100,000	0.1 to -0.1	150	Yes
7	N-2	15	1,000,000	0.01 to -0.01	150	Yes
8	N-3	1.5	100,000	0.1 to -0.1	150	Yes
9	N-5	15	1,000,000	0.01 to -0.01	150	Yes
10	N-6	1.5	100,000	0.1 to -0.1	150	Yes

*pounds of force

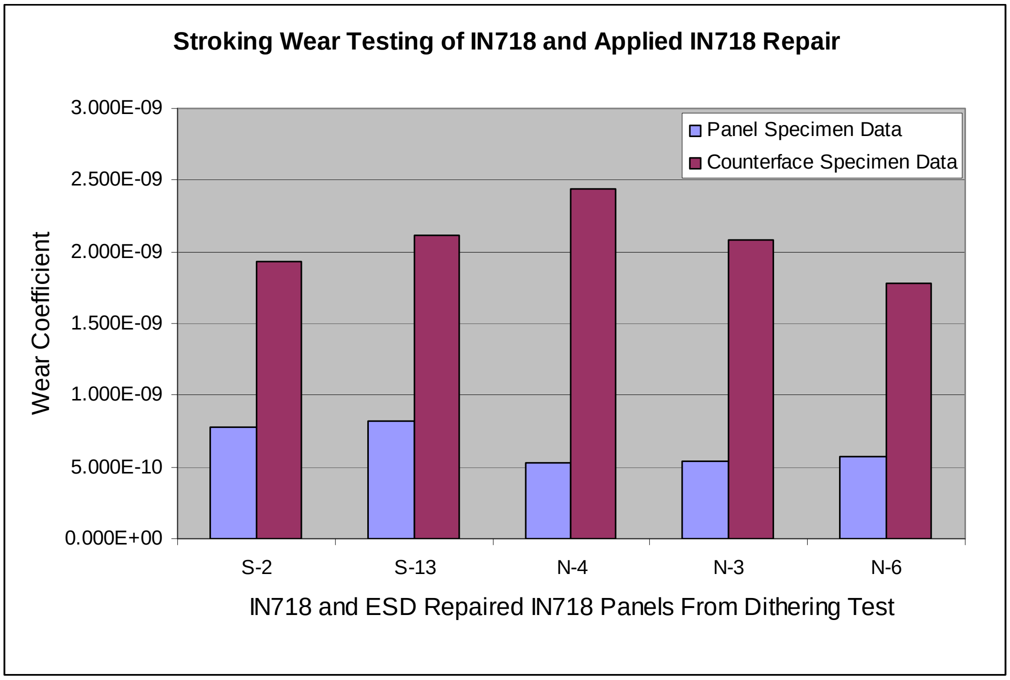


Figure 13. Wear Coefficients of IN718 and ESD-Repaired IN718 Under Sliding Wear Conditions.

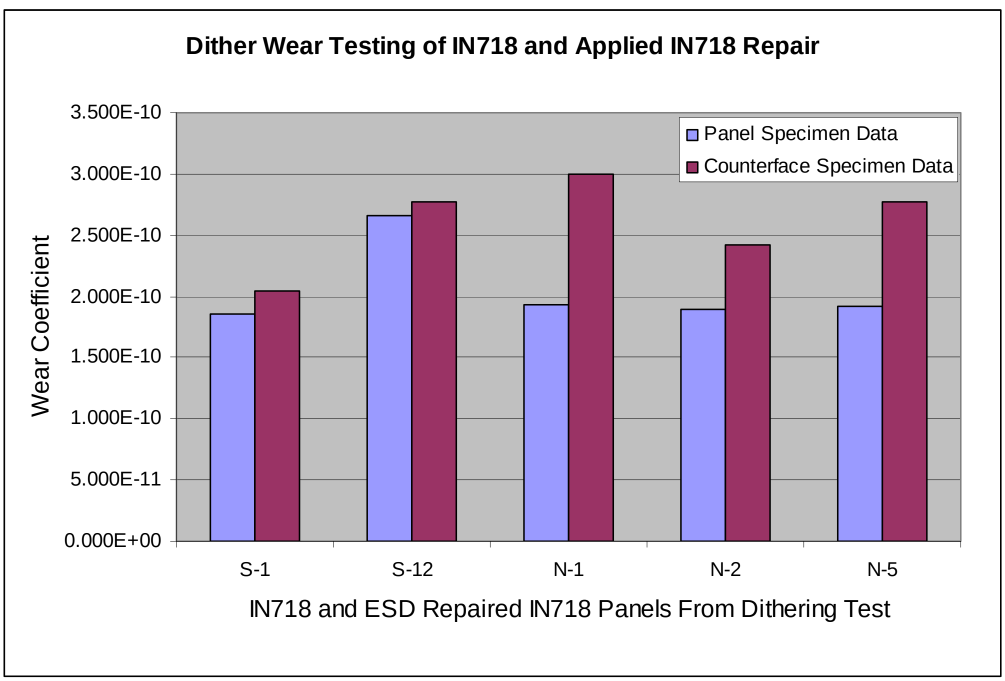


Figure 14. Wear Coefficients of IN718 and ESD-Repaired IN718 Under Fretting.

Corrosion

For all of the specimens exposed to the salt fog in accordance with ASTM B117, no evidence of corrosion was observed either inside or outside the ESD-repaired areas. It was not possible to visually determine where the ESD-repaired areas were, so the coupons were etched to show the location of the repairs. Two of the three specimens subjected to the ASTM G-48 test showed minor pitting corrosion in the ESD-repaired areas but not on the base metal. The third specimen showed no evidence of pitting.

4.3 DATA EVALUATION

All ESD repairs produced a fatigue debit over baseline fatigue life. For ESD repaired divots, the high energy parameter set (V4) produced a greater fatigue debit than did the moderate energy level ESD repairs (#32). This is proof that ESD applied with a higher energy input (and higher deposition rate) negatively affects the fatigue life of the component. The UIT post-ESD treatments increased the fatigue life over ESD-only repairs to near that of baseline life. In the lower stress levels, the fatigue debits are about the same, but at higher stress levels, the bead-on-plate repairs provide less fatigue debit than the divot repairs.

The tensile strength of all specimens was essentially identical. No strength debit was noted for ESD repairs. Ductility was approximately 25% higher for the ESD bead-on-plate condition compared to the divot repair condition. The higher energy ESD treatment, parameter set #V4, resulted in virtually no difference in IN-718 than the lower energy parameter set, #32. This is proof that ESD applied with a higher energy input (and higher deposition rate) does not affect the tensile strength of the component.

The pin-on-disk wear test results indicate that for the ESD parameter set V4, the deposit is less wear-resistant than the parent material. This coincides with the microhardness data. Microhardness and wear resistance both decreased compared to the parent material. For the ESD parameter set #32, the results indicate that the deposit is more wear-resistant than the parent material. However, the microhardness data of this parameter set was less than the parent material. Therefore, a conclusive relationship between microhardness and wear resistance cannot be drawn. Based on the groove depth in the ESD as a percentage of the groove depth in the parent material, #32 with UIT seemed to demonstrate the best wear resistance.

The H-S wear test results indicated that there was little difference in the wear characteristics of the ESD deposit. The ESD performed identically for all parameter sets. In the sliding wear test, #32 exhibited slightly better wear resistance than V4, which mimics the results seen in the pin-on-disk wear test. All panels that were ESD-repaired showed less material loss than the virgin panels, and the wear coefficients were lower than virgin panels. All specimens that were run at dither stroke show a lower level of material loss than the tests that were run at long stroke.

None of the ESD-repaired IN718 coupons showed visible corrosion from the 168-hr salt fog exposure. Two coupons that were subjected to the ASTM G-48 test showed minor pitting corrosion on the ESD deposit but not on the base metal. This test, which is more chemically aggressive than the salt fog test, points out the fact that the ESD deposits are more susceptible to corrosion than the base metal in this type of environment.

4.4 COMPONENT REPAIR ASSESSMENTS

Gas Turbine Engine Components

The objectives of this portion of the project were to demonstrate ESD repairs to damage on actual GTE components, to document the repair procedures, and to transition ESD repairs for use on GTE and other types of components. OC-ALC was the demonstration site identified specifically for GTE components.

A screening matrix was developed to look at what parts may be possible candidates for ESD repair. A preliminary candidate part selection criteria document was designed to record all information on candidate components. Requirements were that the candidate component should be:

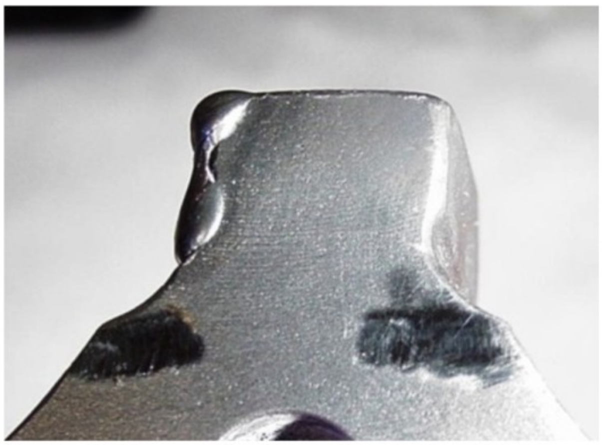
- Non-flight-critical
- Fabricated from one of the materials studied
- One for which no current repair exists for the damage or the existing repair process meets one or more of the following:
    - A process that is not environmentally friendly
    - A process with unsatisfactory results
    - A process that is not conducive to an in situ environment

With input from OC-ALC, as well as Pratt & Whitney (P&W) and GE Aircraft Engines (GEAE), many different components were considered, and through a down-select process, three components were selected: #5 bearing housing, 10-12 stator segment, and TF39 compressor rear shaft.

The #5 bearing housing, part number 71214, is from the TF33 engine. This component is fabricated from 410 stainless steel and requires dimensional restoration (loss of material due to wear). The current repair process is such that if the damage is less than 0.005 in deep, then it is blended away; if the damage is greater than 0.005 in deep, no repair process is available and the part is scrapped. These components are no longer manufactured and, without a repair process, the availability of these components is declining. An ESD repair using a 410 stainless steel electrode would replace the worn material, resulting in a component that has been restored to its original dimensions and with the same wear performance as the initially manufactured component.

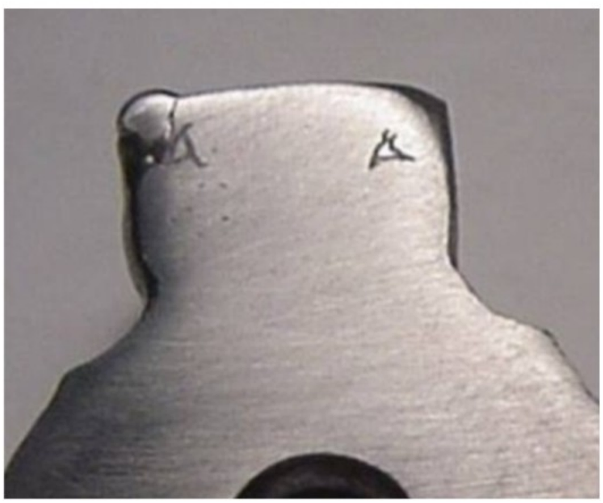
Figure 15 shows the procedure for ESD repair of worn areas in the vicinity of a lug on the component. In the process development, a metallurgical evaluation of the repaired areas was performed. Density measurements were conducted using image analysis which showed an average porosity of 1.7%. The average microhardness of the base material was 633 Knoop whereas the average microhardness of the ESD repair was 606 Knoop. The repaired areas were surface-finished and restored to the original dimensions. OC-ALC reported that the porosity, microhardness, and surface finish results all met their requirements. Welding specification documents were created to facilitate in the implementation of the repair process. One document

provides sufficient information on the ESD process in general to allow an operator to perform the ESD process. Two other documents provide the information necessary for an operator to make the specific repair on this specific component. A hands-on demonstration of the repair was provided to OC-ALC engineers in 2004. The welding specification documents were delivered to OC-ALC at the same time. The technical order (TO) for repair of this component at OC-ALC has been modified to include the ESD repair.



a) Excavate damaged area

b) Repair excavated area



c) Surface finish repair area

d) Perform FPI on repair

Figure 15. No. 5 Bearing Housing Repair.

The 10-12 stage stator segment, part number 4077880, is from the F100 engine. This component is fabricated from Inconel 718 and requires dimensional restoration of deep wear scars that occur on the hook. The damaged area is non-line-of-sight; therefore, many traditional repair processes cannot be used. The current repair process is to cut off the damaged hook and weld a new one in its place, followed by a heat treatment. Because this component is allowed only three heat treat cycles, in many cases the repair process cannot be performed. An ESD repair using an Inconel 718 electrode would dimensionally restore the worn areas without the need for heat treatment, resulting in a component with the acceptable performance.

An ESD repair procedure was developed for the stator segment that consisted of identifying the defective areas, excavating the damage to produce a smooth surface, filling the excavated area using ESD, and then surface finishing back to the original dimension. Since this was a non-line-of-sight application, a custom applicator head was designed that could access the areas under the hooks. Metallurgical evaluations of the repaired areas showed acceptable parameters for porosity, microhardness, and surface finish. A welding specification has not yet been written for this application.

The compressor rear shaft, part number 9103M58G12, is from the TF39 engine. This component is fabricated from Inconel 718 and is chrome plated. There are two types of problems that occur with this part—scratches in the hard chrome plate on the journal and incomplete or damaged chrome plating on the "step" (the area perpendicular to the axis of the shaft, where the outer diameter of the shaft is increased or reduced). The current repair for the chrome plating is to completely strip the coating and replate with hard chrome. An ESD repair of the scratch using a Stellite electrode would eliminate the need to strip and re-chrome the entire journal area. An ESD repair of the step using a Stellite electrode will eliminate the chrome plating process altogether in these areas.

An acceptable repair to the hard chrome plating on this component could not be developed, and a fully dense repair on the hard chrome could not be achieved. Because this is a flight critical component, OC-ALC was not willing to pursue further development work on this part.

Army Tank Components

The M1A1 cannon cradle is fabricated from 4130 steel and is subject to extensive corrosion pitting and wear in service. Many components have to be removed from service, and the rejection rate is an important issue since there is a shortage of available replacement parts. The Army Research Lab (ARL) and the Anniston Army Depot (ANAD) worked together to develop an ESD procedure that would be capable of repairing the damage to the components and returning them to service. In this case, IN718 was selected as the material to be deposited using ESD. Optimized deposition parameters were identified and extensive metallographic and microhardness measurements were taken to ensure a fully dense deposit with a hardness equivalent to that of the base material.

The reclamation procedure for the cannon cradle was approved by ANAD Engineering and has been performed since June 25, 2003. Figure 16 shows the application of an ESD coating to a cannon cradle at ANAD. The total amount of time required for this repair, including surface preparation prior to deposition and finishing subsequent to deposition, has averaged 9 hrs. A formal Reclamation Procedure 03-39 has been developed for repair of this component and is provided in the final report [6]. As of the date of this report, 15 cannon cradles have been repaired. A cursory cost analysis showed that approximately $360,000 has been saved by using ESD to repair the components as opposed to acquiring replacement components.

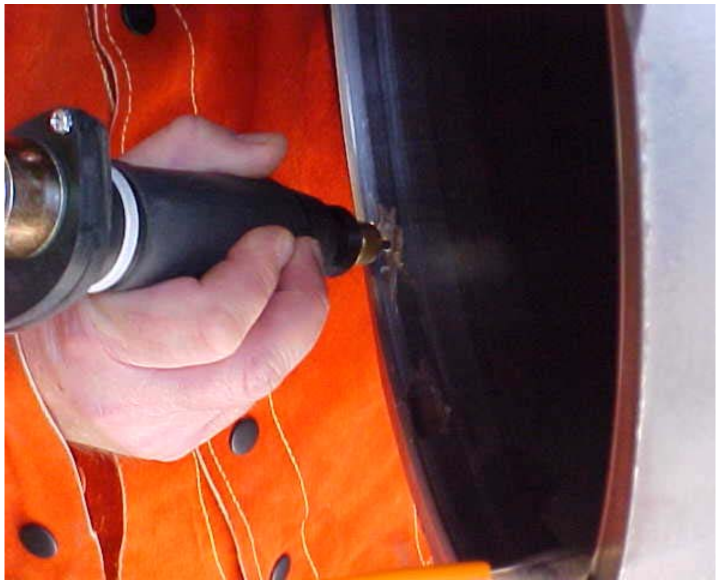


Figure 16. Application of ESD Coating to M1A1 Cannon Cradle.

At the time this report was written, ARL and ANAD were working to develop an ESD repair to an M1A1 helical gear shaft fabricated from 9310 steel onto which hard chrome plating is applied for wear resistance. The problem is that after several years of service wear scars or large corrosion pits are formed and there is no acceptable repair. ARL has demonstrated that ESD can provide acceptable repairs on chrome-plated test coupons in which defects had been machined and has also demonstrated repair of chrome plate on an actual helical gear shaft. Engineering approval for application of ESD to repair this component is dependent on the results of rig tests on an AFT-1500 Engine Test Stand for 100 hrs. In anticipation of approval of this repair procedure, a draft reclamation procedure has been developed.

This represents an example of an apparent successful application of ESD to repair hard chrome plate as opposed to the unsuccessful attempts on the TF39 compressor rear shaft mentioned above. Therefore, it appears that repair of chrome plate on components will have to be handled on a case-by-case basis.

Navy Ship Components

Corrosion and wear of shipboard components exposed to seawater environments are a continual maintenance burden for the U.S. Navy. In many cases, the components are quite large and repair involves removing them from the ship or submarine, which is time-consuming and costly. Quite often the corroded or worn areas are in localized areas on the components, representing a very small fraction of the total surface area on the component.

An example of this is steering and diving control rods on Navy submarines. These rods are fabricated from Alloy K500, a precipitation-hardened nickel-copper alloy with a nominal composition of 63Ni-30Cu-2.5Al-2Fe-1.5Mn (Ti, Si, and C at less than 1%). During service, these rods are subject to wear and corrosion pitting. Generally, the surface damage is limited to small areas on the rods. Another problem area is crevice corrosion in seawater piping systems

fabricated from Alloy 625, which is highly resistant to localized corrosion except in tight crevices. This type of corrosion is often encountered in components such as flanges and valves. As with the control rods, the damage is usually localized but current repairs require that the components be removed from the submarine and overhauled at a repair facility or replaced.

Electrospark deposition was considered to be a potentially ideal technology that could be utilized for repair of the localized damage on these types of components. This was because ESD could deposit coatings in small areas with a metallurgical bond to the base material and because of its portability, which would enable an ESD system to be brought onboard a ship or submarine to effect repairs in situ without having to remove the damaged component. This would provide substantial cost savings as well as significantly reduce turnaround times for repair.

Naval Surface Warfare Center Carderock Division (NSWCCD) conducted materials studies and component demonstrations to validate the ESD process for repair of various ship and submarine components. ESD coatings of Alloy 400 were deposited onto Alloy K500 specimens for GM9540 cyclic corrosion and electrochemical potential measurements. In addition, bend tests performed on ESD coatings showed that there was no flaking, delamination, or cracking of the coatings when bent 180º around a 0.5 in-diameter rod. The electrochemical tests showed that the open circuit potential of the ESD Alloy 400 coatings in simulated sea water was comparable to that of wrought Alloy 400. The GM9540 cyclic corrosion tests showed a slightly higher corrosion rate for the ESD-repaired area compared to base material.

ESD repairs involving deposition of Alloy 400 onto actual Alloy K500 steering/diving control rods were developed. Initially the quality of the deposits was poor, with significant porosity and voids. Working with ASAP, NSWCCD personnel were able to optimize deposition parameters and produce deposits with very little porosity.

As mentioned above, Alloy 625 seawater components were identified as good candidates for ESD repair. For the materials studies, Alloys 59, 686, and C276 were deposited using ESD onto Alloy 625 test specimens. A series of microhardness measurements showed that, within statistical uncertainty, the hardness of the C276 deposits was the same as for conventional wrought Alloy 625. An extensive series of crevice corrosion tests were performed in simulated seawater. After 180 days exposure, ESD-coatings of Alloy 686 and 59 were highly resistant to crevice corrosion, similar to what was observed for control specimens of Alloy 625, 59, 686, and C276. The only specimens to exhibit susceptibility to crevice corrosion were the C276 ESD coatings.

In summary, a laboratory assessment of the ESD process for repairing Navy components was performed. Although corrosion was noted within narrow groove repair areas on the ESD-coated Alloy K500 component, subsequent simulated defect specimens showed that good quality coatings can be deposited using this method. Additionally, on Alloy 625 surfaces there were apparent inconsistencies in coating quality among ESD-coated Ni-Cr-Mo alloys based on the good crevice resistance noted for ESD Alloys 59 and 686 and the crevice susceptibility found on the ESD Alloy C276 specimens after immersion in natural seawater for 180 and 365 days. The ESD process appears feasible for repair of Alloys K500 and 625 Navy components; however,

additional evaluation of electrospark deposition procedures and NDE methods are required to ensure consistent and optimum coating quality.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

The costs and benefits associated with implementing ESD at OC-ALC instead of repairing components using present technologies or shipping them off-site for repair were analyzed. The cost-benefit analysis (CBA) used the Environmental Cost Analysis Methodology (ECAM) [7] and was funded by the PEWG. It considered the feasibility of using ESD to repair the following components: (1) TF33 No. 5 bearing housing, (2) TF39 compressor rear shaft, and (3) F100 10-12 stator segment. Each component evaluated in this analysis has a different baseline repair process that is conducted at a different facility. The TF33 No. 5 bearing housing repair is done at OC-ALC. The F100 10-12 stator segment is repaired at the OEM and the TF39 compressor rear shaft at a commercial repair facility. The names of the repair facilities are not given due to sensitivity of operational data. Baseline data was collected at the repair facility for the TF39 compressor rear shaft. This level of detail for the baseline processes was not available for the other components. The OEM that repairs the F100 10-12 stator segment provided total repair cost (billed to the government) per segment and OC-ALC provided repair costs per housing for the TF33 No. 5 bearing housing. These baseline costs were compared to the estimated process costs for the proposed alternative, ESD, which would be realized upon implementation of this alternative process at OC-ALC. All alternative costs were provided by ASAP, Inc, the company that commercially developed the technology.

Annual maintenance and operating costs were also included in this analysis as were any periodic maintenance costs. Where available and applicable, the following types of information related to the baseline process were collected. Data related to the alternative process were estimated.

- Process flow
- Labor requirements
- Material usage
- Utility usage
- Equipment maintenance costs
- Waste management and disposal costs
- Personal protective equipment (PPE) costs
- Effect on regulatory compliance
- Effect on support facility operations
- Effect on providing and administering training
- Effect on operating and maintaining equipment and facilities
- Other related cost impacts

Baseline process data were collected through a site visit and follow-on data collection via telephone and e-mail. Where data were not available, they were assumed based on engineering judgment.

<u>TF33 No. 5 Bearing Housing Repair</u>

In the past, OC-ALC repaired this component using a weld repair process that involves grinding and weld repairing the worn area. General repair instructions have been issued, but OC-ALC has been unable to identify a process, material, tool, or procedure to consistently produce the

required polish on the mating surfaces of the splines. Presently, OC-ALC is not repairing this component but purchasing replacements. This analysis compares the estimated cost of repairing the components at OC-ALC under the present repair procedure to repairing using ESD. Two alternative cases have also been considered. The first assumes that the average repair requires that six of the 18 lugs on each housing needs to be repaired. The second case assumes that all 18 lugs need to be repaired. The average annual production is 84 housings.

Repair costs were provided by OC-ALC, but since the depot does not track these costs by number of lugs repaired, the baseline cost is an average. The annual costs for repair of this component are $299,300, representing $3,563 per housing.

Detailed data and assumptions used for the analysis of implementation of ESD for repair of this component at OC-ALC were provided in the project Final Report [6]. These included capital costs, operating costs (including labor, utilities, and materials), and environmental, safety and occupational health (ESOH) costs. Table 8 summarizes the operating costs associated with using ESD to repair the housings.

Table 8. Annual Operating Costs for TF33 No. 5 Bearing Housing Repair Using ESD Process.

Resource	Annual Costs
Labor	$131,508
Materials	3,491
Utilities	9,324
Waste Disposal	0
Environmental Management	625
TOTAL ANNUAL OPERATING COSTS	**$144,948**

<u>TF39 Compressor Rear Shaft Repair</u>

The TF39 GTE compressor rear shafts are repaired at a repair facility using chromium electroplating. Repairs include restoring journal diameters and repairing worn shoulders and surface chips. The average number of repairs conducted for this component is as follows:

- Journal diameters: 20 shafts per year
- Shoulders: 6 shafts per year
- Surface chips: 5 shafts per year

The general data and assumptions related to baseline processing of the TF39 components is provided in the project Final Report [6]. Table 9 summarizes the annual operating costs for the baseline chrome plating process. It is important to note that these costs represent only those expected to be impacted by the implementation of ESD; total processing costs are in fact higher. The detailed data and assumptions related to implementation of ESD on these components are provided in the Final Report. Table 10 summarizes the annual operating costs for the ESD process.

Table 9. Annual Operating Costs for TF39 Compressor Rear Shaft Repair Baseline Process at Repair Facility.

Resource	Total TF39 Repair Costs	Total Journal Repair Costs	Total Chip Repair Costs	Total Shoulder Repair Costs
Labor	$75,640	$42,962	$10,741	$21,937
Materials	20,731	16,347	4,087	297
Utilities	7,474	5,893	1,473	107
Waste disposal	2,581	2,035	509	37
EHS	1,309	707	177	424
TOTAL ANNUAL OPERATING COSTS	**$107,735**	**$67,944**	**$16,987**	**$22,802**

Table 10. Annual Operating Costs for TF39 Compressor Rear Shaft Repair Using ESD Process.

Resource	Annual Costs
Labor	$24,730
Materials	154
Utilities	543
Waste disposal	0
Environmental management	139
TOTAL ANNUAL OPERATING COSTS	**$25,566**

<u>F100 10-12 Stator Segment Repair</u>

This component is repaired by shipping to the OEM. It involves cutting off the three hooks on the segment and rewelding on new hooks. The average annual production is 34 segments. Baseline operating costs for repair are based on reported annual quantities and repair costs provided by the overhaul facility. The OEM repair charge is $1,148 per segment for a total annual cost of approximately $39,000.

Detailed data and assumptions related to implementation of ESD for repair of this component are provided in the project Final Report [6]. Table 11 summarizes the annual operating costs for the ESD alternative.

Table 11. Annual Operating Costs for F100 10-12 Stator Segment Repair Using ESD Process.

Resource	Annual Costs
Labor	$6,460
Materials	(332)
Utilities	(1,486)
Waste disposal	0
Environmental management	(625)
TOTAL ANNUAL OPERATING COSTS	**$ 4,017**

5.2 COST ANALYSIS

This CBA was performed using the Pollution Prevention Financial Analysis and Cost Evaluation System (P2/FINANCE) software, which generates financial indicators that describe the expected performance of a capital investment. A brief explanation on interpreting these financial indicators is provided, as are the results of the financial analyses for the implementation of the alternative process at OC-ALC.

To measure the financial viability of this project, three performance measures for investment opportunities were used: net present value (NPV), internal rate of return (IRR), and payback period. The NPV is the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. The IRR is the discount rate at which NPV is equal to zero. The payback period is the time period required to recover all the capital investment with future savings.

These financial indicators account for the time value of money and discount the future capital investments or annual cost benefits to the current year. A 2.7% discount rate was used for this financial evaluation, which is consistent with the Office of Management and Budget (OMB) Circular Number A-94 and the ECAM. This circular provides specific guidance on the discount rates to be applied in any analysis used to support government decisions to initiate, renew, or expand programs or projects that would result in a series of measurable benefits or costs extending for 3 or more years into the future.

The costs given above in the report were entered into the P2/FINANCE software, and financial indicators were calculated. The results are provided in Table 12 through Table 15.

Table 12. Results of Financial Evaluation for TF33 No. 5 Bearing Housing Repair—Case 1: Six Lugs Repaired.

Financial Indicator	5-year	10-year	15-year
NPV	$ 655,421	$1,272,267	$1,815,285
IRR	288.2%	288.5%	288.5%
Discounted payback	0.36 years		

Table 13. Results of Financial Evaluation for TF33 No. 5 Bearing Housing Repair—Case 2: 12 Lugs Repaired

Financial Indicator	5-year	10-year	15-year
NPV	($535,437)	($960,927)	($1,330,247)
IRR	N/A	N/A	N/A
Discounted payback	N/A		

Table 14. Results of Financial Evaluation for TF39 Compressor Rear Shaft Repair.

Financial Indicator	5-year	10-year	15-year
NPV	$10,461	$64,774	$113,693
IRR	9.3%	22.4%	24.9%
Discounted payback	4.16 years		

Table 15. Results of Financial Evaluation for F100 10-12 Stator Segment Repair.

Financial Indicator	5-year	10-year	15-year
NPV	($36,719)	($23,667)	($10,864)
IRR	N/A	N/A	N/A
Discounted payback	N/A		

N/A: Not applicable—could not be calculated as return on investment (ROI) was not realized

This analysis estimated the annual operating costs associated with implementation of ESD in place of various baseline repair processes. Implementing ESD in place of chromium electroplating had the most benefits, including a savings in labor, materials, waste disposal, and environmental, safety and health costs. Implementation of ESD for weld repair of the TF33 No. 5 bearing housing and the F100 10-12 stator segment is expected to show a slight decrease in annual operating costs. This analysis indicated that using ESD to repair six or fewer lugs on the housing (Case 1) is less expensive than the present repair procedure. However, if all 18 lugs need repair (Case 2), then the present repair procedure is more cost-effective than ESD. The 15-year NPV for the TF33 No. 5 bearing housing is $1.8 million for Case 1 and ($1.3) million for Case 2.

The break-even point for ESD is 12 or fewer lugs per housing needing repair. However, OC-ALC has been unable to identify a sufficient repair procedure. Implementing ESD is therefore dependent on whether OC-ALC feels that it is a better option than purchasing new components.

For the TF39 compressor rear shaft, the 15-year NPV is $113,700 with a 4.2-year payback period. Although implementing ESD for the F100 10-12 stator segment is expected to result in a $4,000 per year savings, the capital expenditures would not be recouped within the 15-year study period. Therefore, the 15-year NPV is negative: ($10,900).

To measure the full benefit derived from ESD implementation, it is necessary to determine the benefit for the entire PEWG propulsion industrial base. In this case, the industrial base is limited to OC-ALC, as it is the only facility overhauling the engines that use these parts. To assist in quantifying this, a rough order of magnitude ROI calculation was done using the project costs. These project costs include all monies budgeted for the various tasks of the project, such as identifying potential alternative and any testing deemed necessary to validate the alternatives. For this calculation, Case 1 for the bearing hosing was used (i.e., six lugs needing repair). The time period expected to obtain a full ROI for the ESD project costs of $1.1 million would be 7.5 years.

ESD has been shown to have financial benefits when implemented in place of existing repair processes; however, each repair needs to be evaluated separately to determine if ESD is economically feasible.

5.3 COST COMPARISON

For the TF33 No. 5 Bearing Housing, as indicated in Section 5.1, the average annual production is 84 housings at OC-ALC. The current average cost for repair of the housings is $3,563 each whereas, based on the CBA, the average cost for repair of the housings using ESD would be $1,725 each, representing a cost savings of $1,838 per housing.

Although ESD deposition parameters were not able to be established to repair the hard chrome plating on the TF39 compressor rear shaft, the CBA did indicate that if acceptable parameters could be developed, cost savings would be realized. Currently, journals are repaired on 20 shafts per year, shoulders are repaired on 6 shafts per year, and surface chips are repaired on 5 shafts per year for a total cost of $107,734, or an average cost of $3,475 per shaft. Based on the CBA, the total cost for performing ESD repairs on the 31 shafts would be $25,566, or an average cost of $825 per shaft. This represents a cost savings of $2,650 per shaft.

For the F100 10-12 stator segment, the average annual production is 34 segments. The current average cost for repair of the segments is $1,148 each whereas, based on the CBA, the average cost for repair of the segments using ESD would be $118 each, representing a cost savings of $1,030 per segment.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The CBA carried out for ESD showed that it is very cost-effective for small areas but not for large areas because of its slow deposition rate. This is clearly seen in the analysis of the TF33 #5 bearing housing where the repair is highly cost-effective for repairing a few lugs on each component but not for more extensive repairs. The cost analysis model findings are borne out by the application to gun cradles at ANAD where the component can be reclaimed by repairing a few small corroded areas on a large diameter.

Significant improvements in ESOH compliance could also be obtained by using ESD to repair limited areas on large chrome-plated components rather than stripping, repairing, and reapplying the hard chrome. However, as indicated in Section 4 regarding the TF39 compressor rear shaft, acceptable repairs of hard chrome plate may not always be able to be developed. Each application must be developed on a case-by-case basis.

6.2 PERFORMANCE OBSERVATIONS

The process development and testing done in this program clearly show that high quality ESD materials can be used for dimensional reclamation and can provide performance similar to that of the original material.

- If the deposition parameters are correctly chosen, ESD coatings can reduce fatigue below what would result from excavating the damage and using no fill (or presumably a low strength fill such as epoxy), i.e., they can restore some but not all of the original strength of the material.
- Whether the ESD coating is as hard and wear-resistant as the parent material depends on how the alloy must be heat treated. Some heat treatments may be approximated by the deposition and quenching of the ESD alloy but others cannot. For many materials, the hardness and wear of the ESD is essentially that of the parent material.
- In general, the corrosion performance of ESD alloys is similar to that of the parent, provided the material is deposited without high porosity into which fluids can penetrate.

6.3 SCALE-UP

There are essentially no scale-up issues associated with the ESD technology because of the size and portability of the equipment and nature of the types of repairs to be performed. Because of the low deposition rates, the technology is most effective for small-area repairs, whether on small or large components. The equipment is portable and capable of being taken out into the field as long as electrical power is available.

6.4 LESSONS LEARNED—ADVANTAGES AND DRAWBACKS OF THE ESD TECHNOLOGY

For depot repair, ESD has a number of obvious advantages:

- The process is easy to learn and can be carried out by depot artisans with a minimum of additional training.
- The equipment is inexpensive and highly portable. Thus it can be used shipboard or at operational bases to carry out repairs of reasonable quality, often without the need to remove items from the system. This has a large potential for cost savings in vehicles, ships, submarines and support equipment (including aircraft support).
- The process is clean, with no significant effluent or waste.
- ESD is a good way to repair damage in a small area of a large component and as such has been shown to be able to repair damaged chrome without the need for stripping and replating, for a significant ESOH saving.

All these advantages make it ideal for depot repair and operational maintenance. As this program has demonstrated, however, the process also has certain drawbacks that inhibit depot use, especially in aerospace overhaul and repair:

- In common with most other widely used welding techniques, the technology is usually manual, making it difficult to ensure a high level of control. A robot can be employed, but this makes the process more expensive and cumbersome, and eliminates the advantage of portability.
- The quality of the interface and the ESD layer is variable, especially in terms of porosity and discontinuities.
- The combination of interface voids and tensile stress in the ESD layer is a concern for aerospace engineers because of the possible impact on fatigue. This inhibits its specification for repair of rotating GTE components.
- When repairing chrome plating, there is a tendency to form a “halo” of voids and discontinuities around the repaired area at the ESD/chrome plating interface.

Ultrasonic impact treatment has been shown to have a very positive effect on the structure of ESD coatings. However, it is seen by aerospace engineers as a crude process that would need to be carefully evaluated and characterized before being applied to aerospace components (although one might argue that it is no more crude than shot peening or low plasticity burnishing). Furthermore, it cannot be used in conjunction with manual ESD or in areas that are not readily accessible. This means that, in general, the ESD material must function adequately by itself. This is especially true if it is to be readily employed by depot artisans in depot- and operational-level maintenance.

6.5 END-USER/OEM ISSUES

OC-ALC was the lead demonstration overhaul facility with work also being done at NSWCCD and ANAD. Each location was equipped with an ESD system from ASAP.

<u>Vehicles—Anniston Army Depot</u>

The process has already been qualified and put into production at ANAD, and its use there appears likely to grow as depot personnel become more acquainted with the process.

- The first qualified repair is the repair of corrosion pits in the Abrams gun cradle. This repair is now in regular use, successfully repairing about one cradle per month, for an annual saving of about $300,000. Although this component would otherwise be condemned rather than stripped, repaired, and rechromed, it demonstrates the use of ESD as a chrome repair. It is also important to note that the repair was developed by depot engineers and artisans with very little input from outside. This illustrates that ESD could be a very powerful tool for depot use in reclaiming components that would otherwise be condemned.
- The second repair at ANAD is repair of pitted areas in an M1A1 turbine engine helical gear shaft. The ESD repair appears to work very well, and again, the repair is made on a chrome plated area without the need to strip and replate the chrome. It is likely to be approved if a repaired shaft passes a 100-hr engine test. This repair illustrates the important point that ESD can be used for repair of rotating GTE components, provided they are not flight-critical. Thus, while Tinker Air Force Base would not be able to use such a repair without extensive (and very expensive) validation and qualification testing, it can be introduced for vehicle (and presumably also for ship and stationary) gas turbines with far greater ease.

Vehicle repair appears to be one of the best applications for the technology since the risks are lowest. Potential applications include:

- Worn or corroded components where the repair area is small and the replacement cost is high, or where the item is no longer manufactured.
- Hydraulic actuators, which are used on a large number of Army earth-moving and loading machinery, and which tend to become corroded and pitted.
- Diesel and turbine engine components for vehicles.
- Turbine engine components for stationary (power) turbines.

<u>Ships and submarines—Carderock</u>

The technology has shown itself to be promising, but there are some issues that must be solved if it is to be a viable repair option:

- A primary issue in development work at Carderock was the halo of porosity created around the repair location. ASAP has now developed methods that appear to minimize, and perhaps completely eliminate, this problem.
- One of the ESD Monel alloys (C276) suffered severe crevice corrosion although the others (Alloys 59 and 686) performed essentially as well as bulk Monel. It is not clear whether this was a result of severe interface porosity or of the ESD alloy having a greater sensitivity.

Carderock concluded that ESD has promise but that a significant amount of work is needed to develop the technology to ensure consistently high quality repairs.

Although the Carderock work left a number of questions unanswered, there would appear to be a high potential for application in ships and submarines where the area to be repaired is small, or even where it is large but where removing the component for repair would be very costly and time-consuming. Examples include:

- Hydraulic, power, drive, pump, and propeller shafts in submarines, where removal and repair is difficult and expensive. In most cases, the ability to effect repairs in cramped spaces with the component in place would appear to be particularly applicable to ships and submarines. As with vehicles, qualification should be much easier than with aircraft.
- Aircraft carrier steam plants, valves, etc.
- Valves and other components in shipboard systems, especially where these items must be repaired at sea.

Learning to apply ESD is easy and the equipment takes up minimal space, making ESD advantageous for at-sea repairs.

To be used in marine applications, the coating methods must be perfected for Monels and similar corrosion-resistant materials. It will be especially important to demonstrate that repairs can be made using ESD alloys that are resistant to crevice corrosion and that can be deposited with good quality (low porosity) interfaces.

Aircraft GTEs—OC-ALC

The reason for designating OC-ALC, the Air Force Engine Repair Depot, as the primary location was that Rolls Royce had implemented the technology for repair of nonrotating engine components that were mismachined or otherwise damaged in manufacture. The reason for their use of ESD only on nonrotating components was concern over the possibility of cracking and of a fatigue debit that the process was seen to have produced in their original testing. Seeing the success at Rolls, the other OEMs and OC-ALC were very interested in its possibilities.
Repairs were developed and demonstrated for several components:

1. Bearing housing for dimensional restoration of the #5 bearing—TF33 engine

2. Compressor rear shaft repair—TF39 engine
3. Repair of 10-12 stator segment—F100 engine.

Of these, the #5 bearing housing is the only one that has been qualified at this point. The TO has been modified to permit this repair, which had a very high cost-benefit if the extent of repair was limited.

The primary barrier to the use of the technology for aircraft GTE repairs is the very high cost of qualification and testing followed by the extensive paperwork required for TO changes and OEM acceptance. GTE repairs must be accepted both by the depot and the OEM, and the cost of the time and paperwork alone is the major cost component. If an engine test is required, the cost can be well in excess of $1 million, making a change practicable only if testing can be piggy-backed onto existing engine tests. In addition, OEM acceptance depends very strongly on whether ESD is defined as a coating, not a weld, since acceptance and qualification of a weld method is much more difficult.

It has been repeatedly emphasized that the easiest way to gain acceptance and adoption of the technology for Air Force GTE repair is through the Materials Review Board (MRB) system. Whenever a component cannot be repaired by standard TO methods, the component is evaluated by an MRB engineer to determine if a repair can be made or if the component must be condemned. In order to use it, MRB engineers must be aware of the capability of the technology and see it as a method they can draw on for repairs where there are no other qualified repairs already specified in the TO.

Another aircraft-related area in which ESD could probably contribute is the repair of corrosion and wear damage on aircraft ground support equipment, such as generators, compressors, bomb and missile loading systems, and the many other vehicles and equipment items needed to support land- and carrier-based flight operations.

6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

There are virtually no regulatory compliance issues associated with the ESD technology. It should be viewed similarly to any other welding process from the standpoint that vapors may be emitted during coatings application. Studies have shown that during deposition of chromium-containing alloys, there is no detectable level of hexavalent chromium in the air in the vicinity of the ESD applicator [8]. For most applications, to prevent oxidation of the deposited metals or alloys, a shroud is place around the workpiece, with an inert gas being inserted into the shroud. This further limits the exposure of operators to any vapors emitted by the ESD process.

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7.0 REFERENCES

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APPENDIX A

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